Predictive Models for Integrated Manufacturing and Structural Performance of Carbon Fiber Composites for Automotive Applications

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General Motors

2018 Annual Merit Review

June 19, 2018

Project ID: MAT117

Overview

Timeline

- Project Start Date: May 1, 2015
- Project End Date: April 30, 2019
- Percent Complete: 75 %

Budget

- Total project funding
  - DOE Share: $6,000,00
  - Contractor Share: $2,571,253
- Funding for FY 2017:
  - DOE Share: $1,177,715
    Contractor Share: $504,735
- Funding for FY 2018:
  - DOE share: $1,820,135
  - Contractor share: $780,058

Barriers

A. ***Manufacturing Technology:*** Stochastic manufacturing simulation tools to predict the outcome within 15% of experimental results to reduce cost.

B. ***Performance Technology:*** Stochastic structural performance simulation to predict the outcome within 15% of experimental results to optimize design.

C. ***Integrated Technology:*** Integrative manufacturing and structural performance simulation tool that can be used in upfront design to deliver the required assembly performance without any trial and error.

Participants

General Motors
Continental Structural Plastics (CSP)
ESI Group, NA
Altair
University of Southern California

Relevance

Predictive Integrated Modeling Tools

- Primary deliverable: An ICME model capable of predicting stochastic manufacturing and structural performance of carbon fiber (CF) composites.
  - Reduce the cost of manufacturing of CF reinforced automotive components by eliminating trial and error through improved manufacturing simulations.
  - Design, optimize and validate the CF automotive structures in a virtual design space through improved performance modeling.
  - Reduce the lead time and cost to design and implement large scale structural automotive composites.
  - Enable the usage of CF composites for significant light-weighting of automobiles and thus improve fuel economy, and lower emissions, which will reduce greenhouse gas emissions.

Cost Barrier

- Will demonstrate the ability to manufacture the automotive CF composites at no more than **$4.32** cost per pound weight saved to address the DOE 2030 targets.

Performance Barrier

- Will demonstrate the viability of CF composites to meet vehicle performance requirements while reducing vehicle assembly weight **(35% lighter)** compared to a current steel design.

Relevance

Steps in implementing CF in automobiles

Current

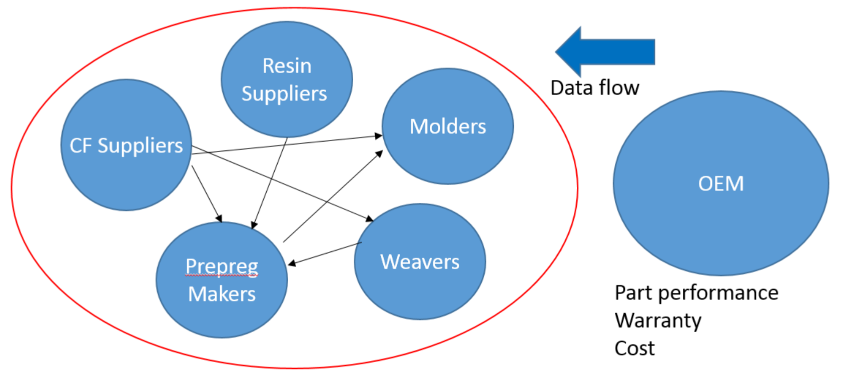
- Design.
- Selection of manufacturing process.
- Manufacturing feasibility.
- Prototype build and learn.
- Modify design and manufacturing process, if needed.
- Improve prototype build and make part.
- Extrapolate to high volume manufacturing.
- Build the part, iterate to get good quality.
- Evaluate the performance and compare with requirements.
- If failure occurs, redesign the part.

Future

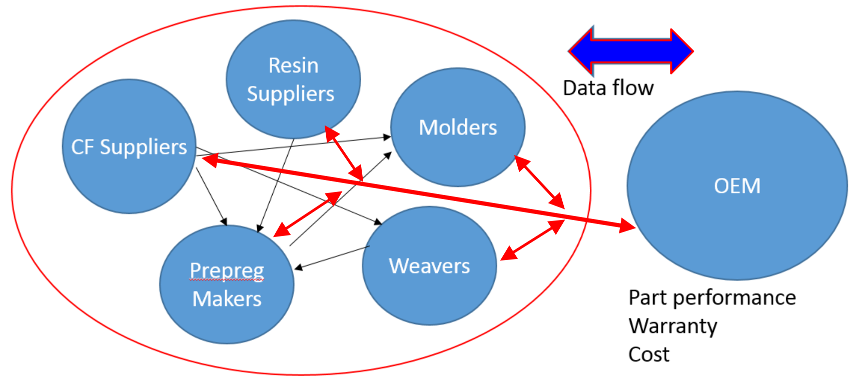
- Design.
- Virtual manufacturing simulation and improve the design for optimizing the cost.
- Include manufacturing outcome in performance simulation and further optimize the design to meet the requirements.
- Build tools, manufacture parts and check the performance

Work flow between OEM and Suppliers

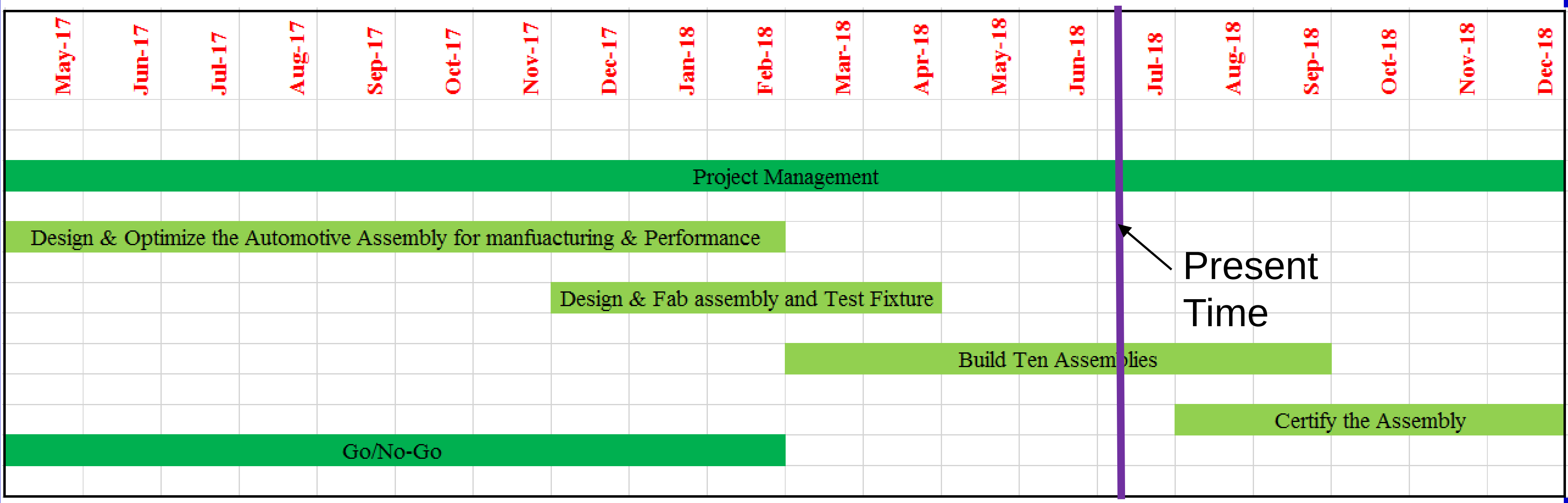
Current



Future



Milestones



All milestones for year 2018 are complete.
Go/No-Go decision was also complete.

Approach/Strategy

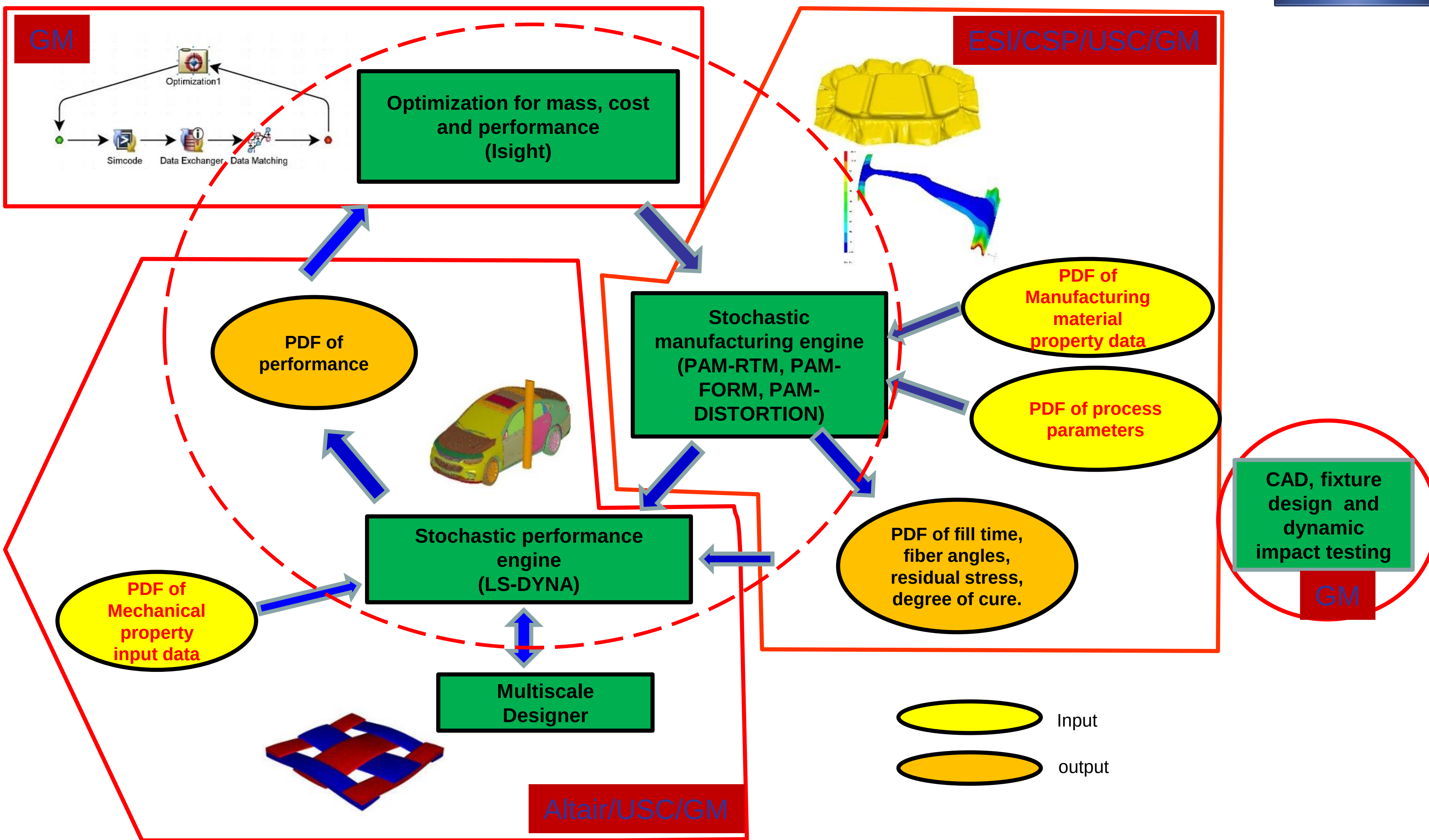
- An ICME approach to develop
  - computational methodologies and tools for predicting stochastic manufacturing.
  - computational methodologies and tools for predicting stochastic performance.
  - Integrated tools to predict the performance of an assembly.

- A team comprised of an automobile OEM, a Tier 1 composite system supplier and molder, software simulation companies in the areas of composite manufacturing and performance prediction, and a DOE funded SciDAC institute for uncertainty quantification.

- **Composite System Supplier**: Responsible for selecting materials and manufacturing processes for high volume manufacturing, providing plaques and coupons for generating the data required for model calibration and validation.
- **Software Companies:** Responsible for the development of predictive tools for manufacturing and structural performance
- **Stochastic Modeling Research Group:** Responsible for developing stochastic models for both manufacturing and structural performance
- **OEM:** Responsible for developing and conducting experiments for model confirmation, integrating the manufacturing and structural performance tools, demonstrating the technology by design, optimizing, building and testing a carbon fiber automotive assembly as well as validating the developed models by comparing the predictions with experimental results.

Approach/Strategy

Developed a process flow of tool development



Accomplishments

FY 17 Accomplishments

Manufacturing simulation tool development and validation

- Draping model development and validation for non-crimp fabrics.
- Development and validation of resin curing model for state of the art resin from Hexion
- Engineer the HP-RTM process design for two major components and C-RTM process design for other two major components of the automotive assembly planned for demonstration.

Stochastic manufacturing simulation tool development

- Stochastic model results for the complete steps of resin transfer molding – draping, injection, curing, etc.
- Complete the development of stochastic manufacturing suite and implement on GM-HPC platform

Structural simulation tool development and validation

- Component validation for a brittle and ductile lay-up
- ICME simulation of truncated pyramid (manufacturing and structural behavior)
- Engineer the structural design for the automotive assembly chosen for the demonstration.

Stochastic structural simulation tool development

- Stochastic structural performance at the component level
- Stochastic structural performance of the automotive assembly

Cost models for the automotive assembly chosen for demonstration

Design and build an assembly fixture for the carbon fiber assembly

Accomplishments

- 5 patents submitted to Government Patent office.

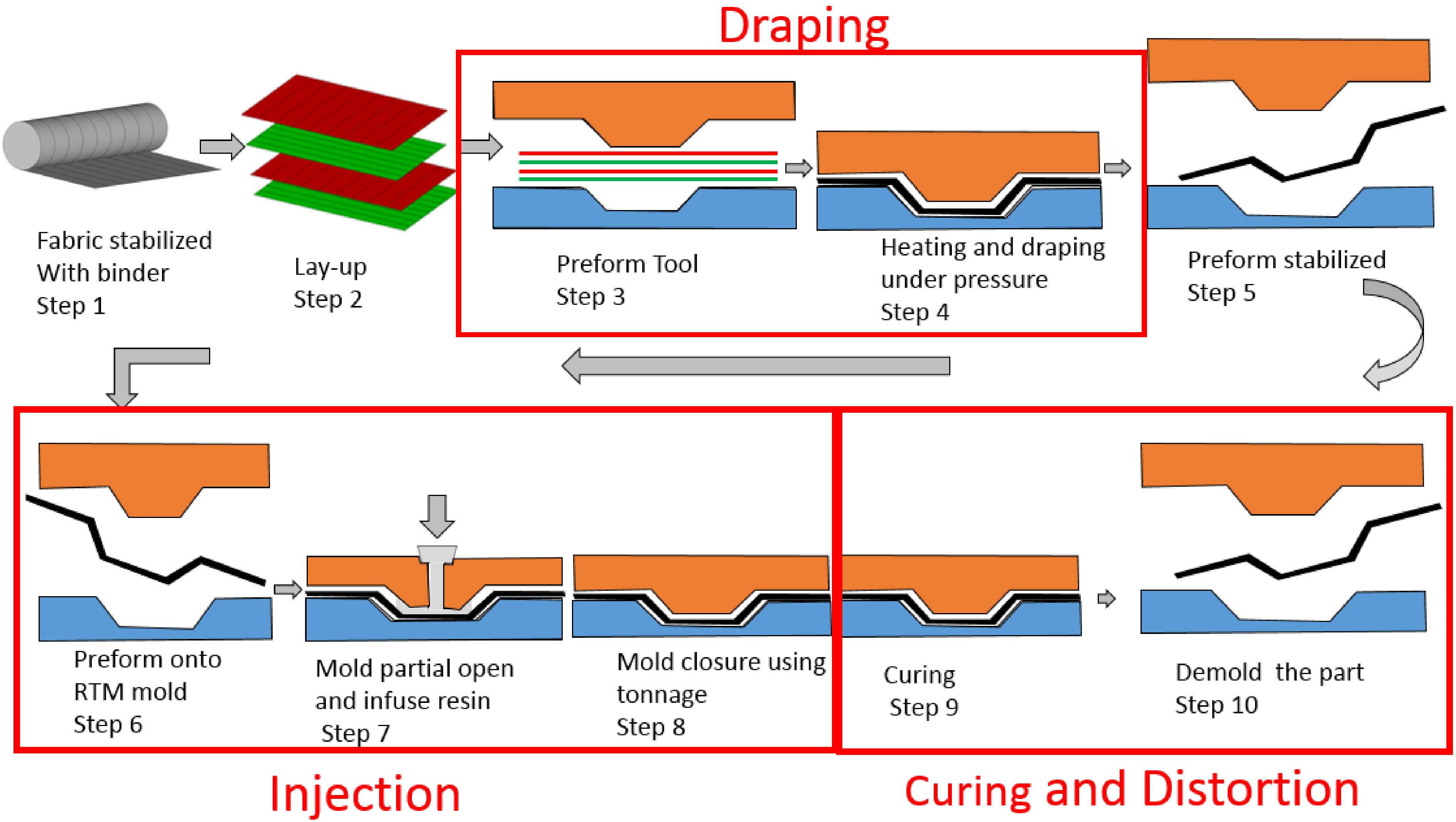
Facilities:

- HP-RTM facility at CSP was upgraded to manufacture components for the assembly. The facility is being moved from CSP France to CSP HQ, MI. Three components of the assembly will be molded at the CSP facility.
- HP-RTM facility being installed at GM R&D. One assembly component will be molded at GM.

Outreach:

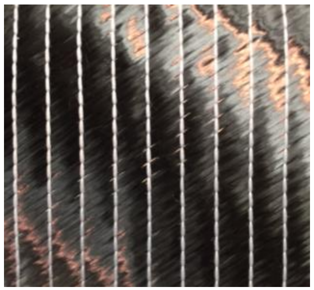
- To meet the project objectives, strategic agreements were put in place to take the advantage of the state-of-the-art resin from Hexion and novel fabric architectures from Teijin and Chomarat.

Manufacturing Process

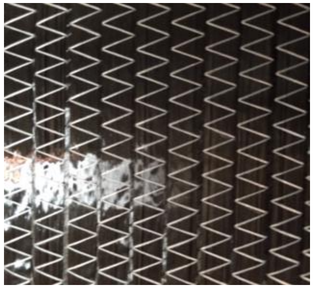


Draping Simulations

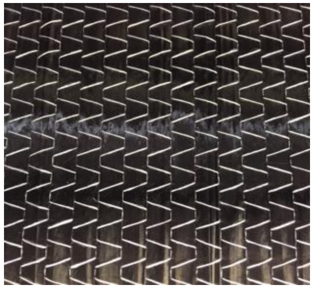
- Non-crimp fabrics (NCF) offer economic advantages compared to woven fabrics, but are limited by a perceived lack of drapeability.
- Accurate predictability of draping is essential to modify the design variables, processing conditions, and fabric production.
- Stitch pattern – Three basic patterns used to make NCFs



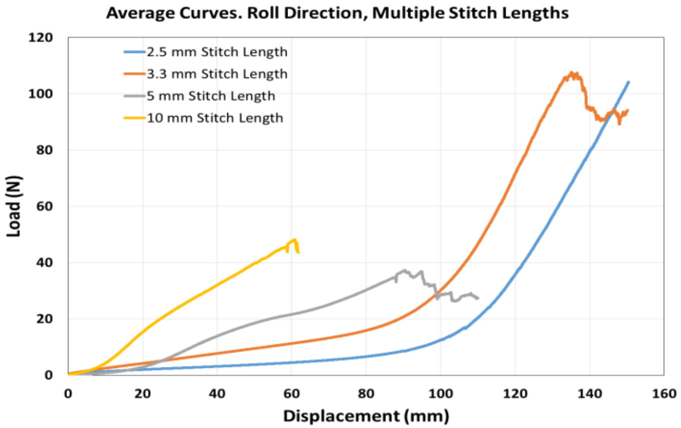
Chain or pillar



Tricot



Hybrid (combination of chain and tricot)



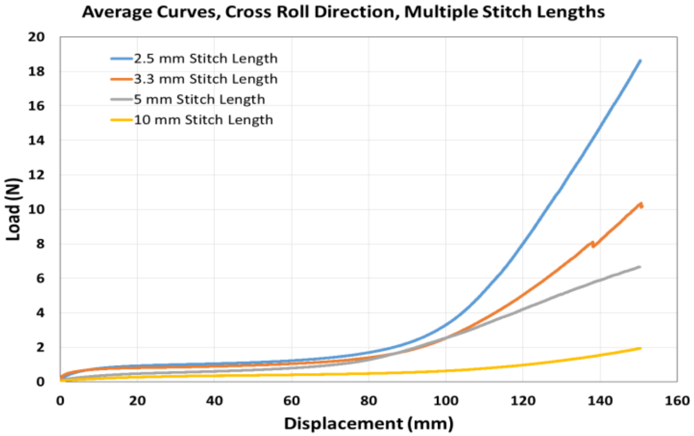
Characterization

2.5 mm Roll

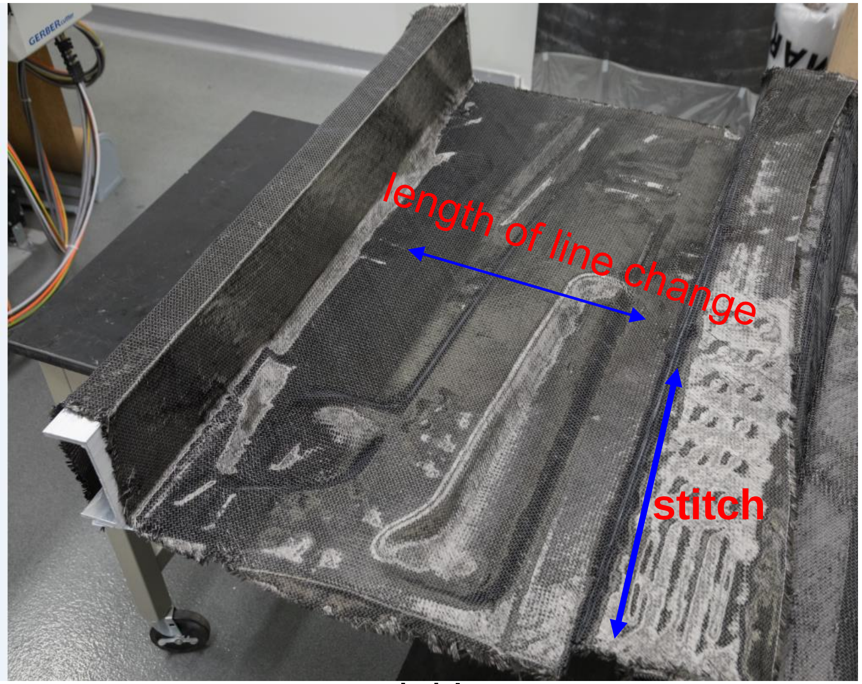
2.5 mm Cross

10 mm Roll

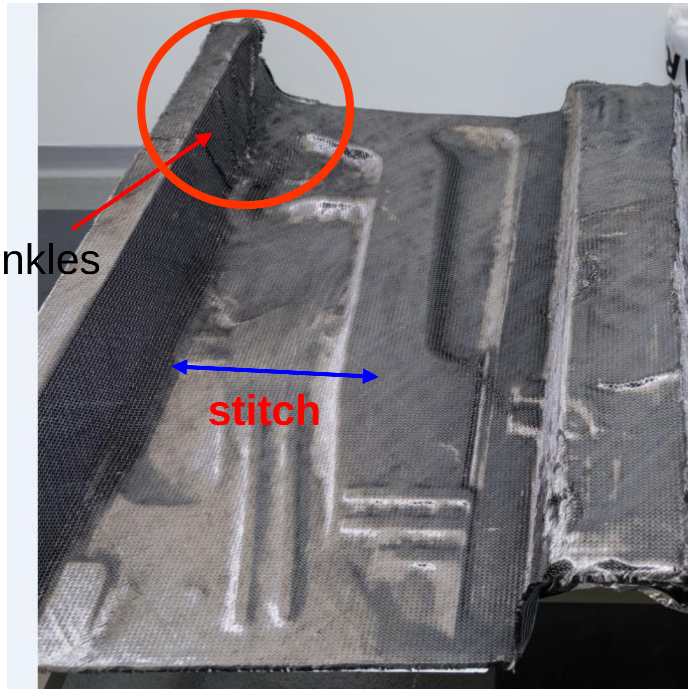
10 mm Cross



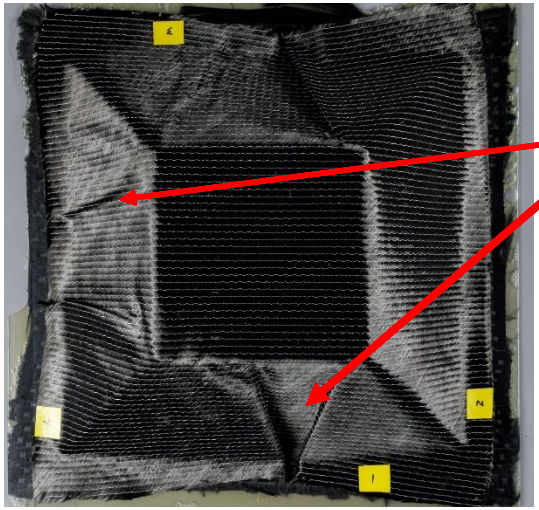
Draping Experiments – Effect of Stich Direction



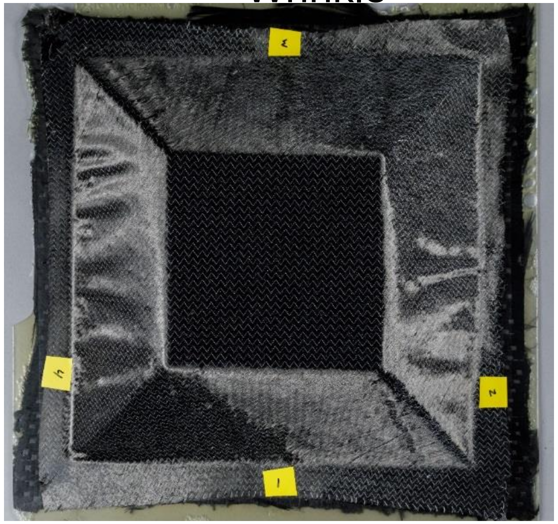
No wrinkles



Wrinkle



No Blank Holder



With Blank Holder

240 gsm
Veil binder

Three Modeling Approaches

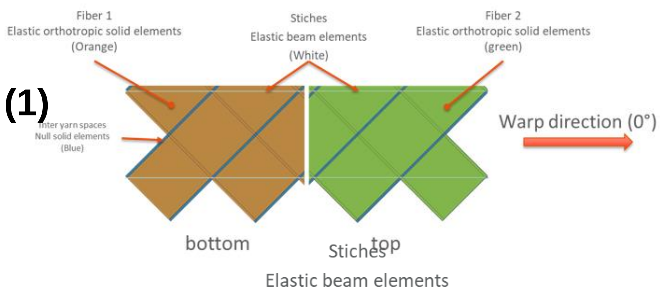
1. Meso-scale approach	2. Hybrid	3. Macro-scale
• 3D solid elements for yarns • 1D beam elements for stitching • Contact definition for interaction between yarn and stitching	• 2D Shell elements for the ply • 1D beam elements for stitching • 1D and 2D meshes linked with tied elements	• 2D Shell elements for the ply • Influence of stitching taken into accounts with different shear behavior for positive and negative shear

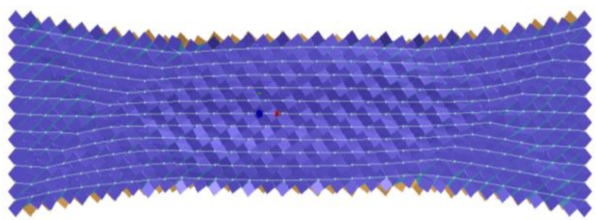
Modeling

Calibration

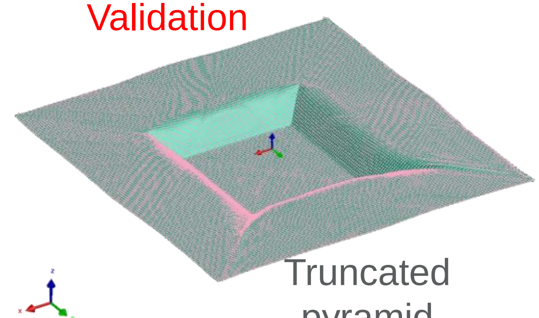
Validation

(1)



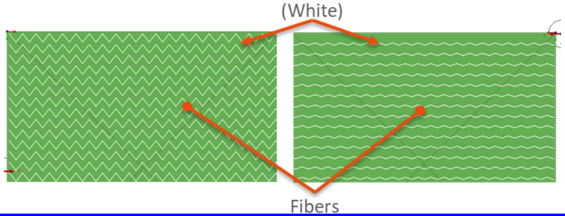


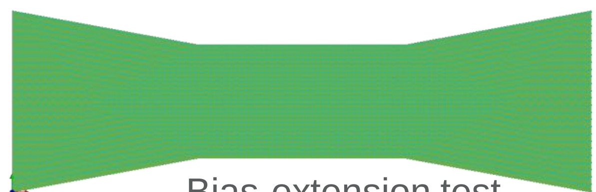
Bias-extension test



Truncated pyramid

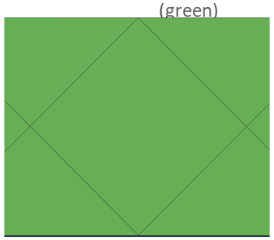
(2)

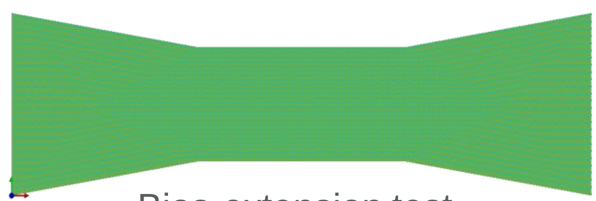




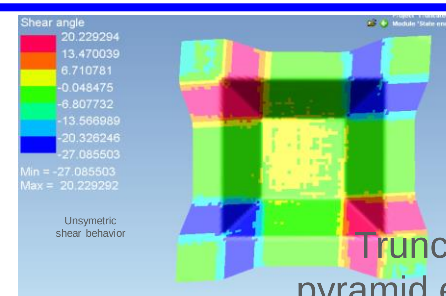
Bias-extension test

(3)





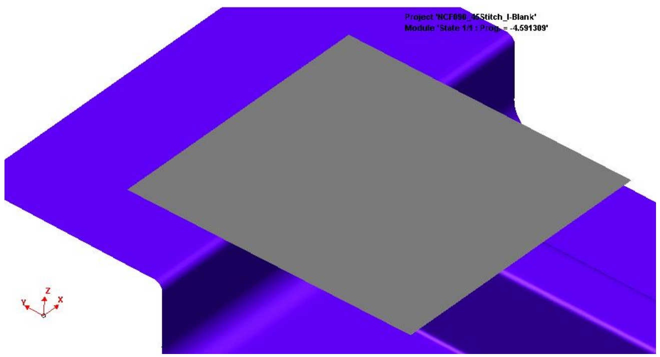
Bias-extension test

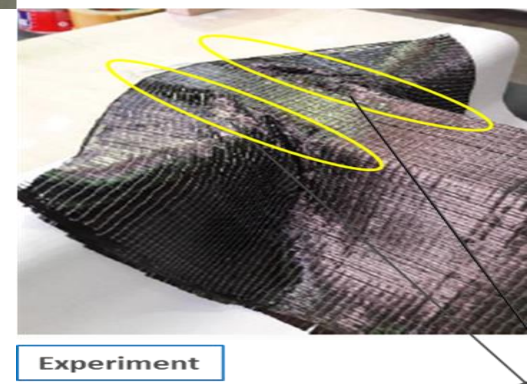


Truncated pyramid example

Validation of Draping Models

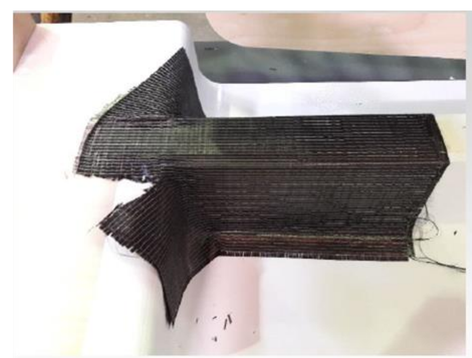
Without slits





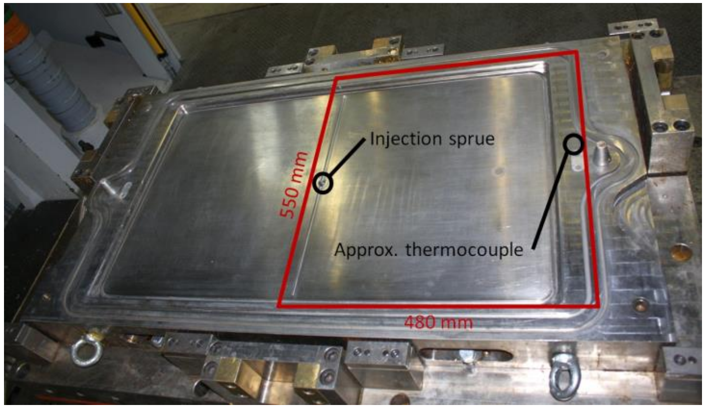
Experiment

With slits

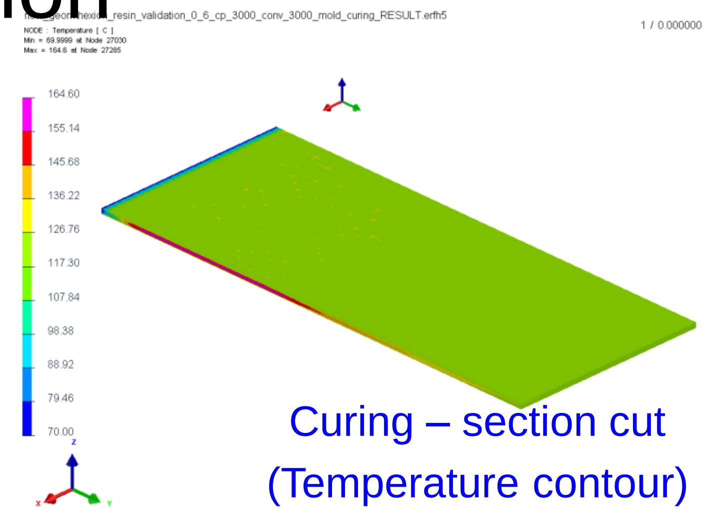


Experiment

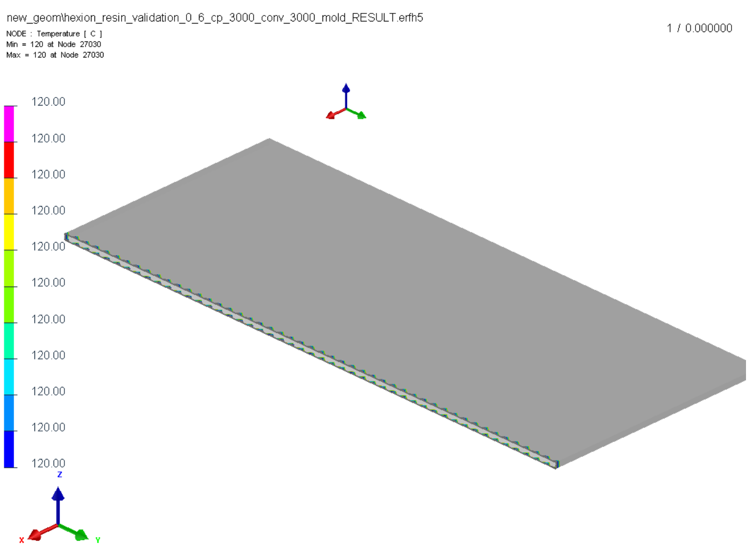
Hexion Fast Curing Resin- Model Validation



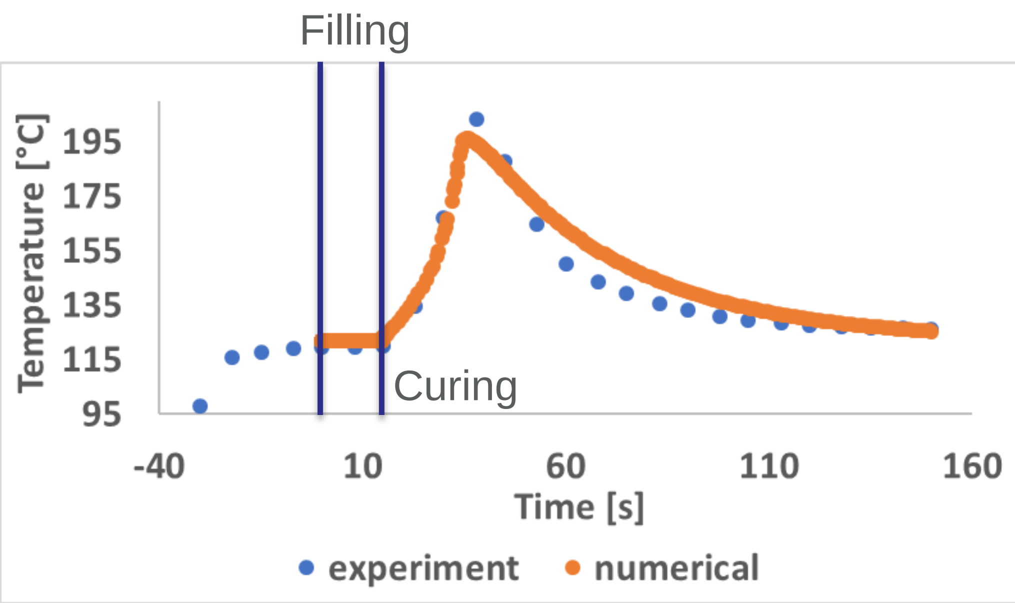
CSP- Europe Experimental setup



Curing – section cut
(Temperature contour)



Filling – Section cut
(Temperature contour)

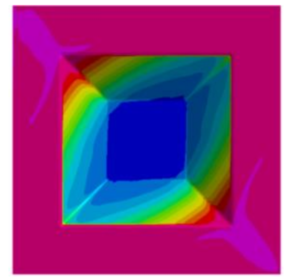


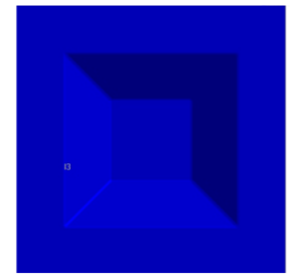
Validation

Stochastic Manufacturing - Draping, Injection, Curing and Distortion

Draping → Injection → Curing → Distortion

Fiber Orientations, permeability as function of Orientation





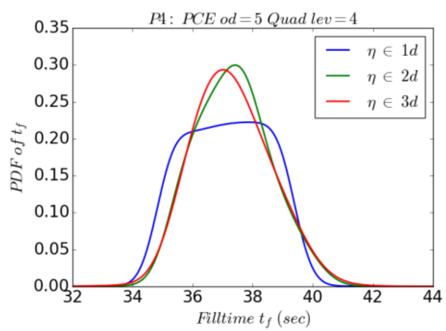
Stochastic Variables

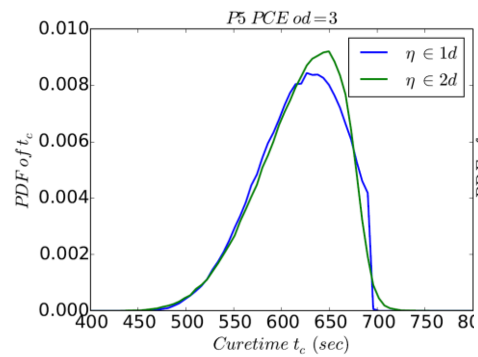
Draping:
Initial orientation of fabric (5D)
Elasticity of fibers (4D)
Draping process (2D)

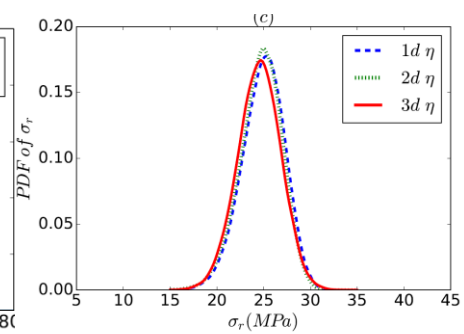
Injection:
Mechanical and thermal properties of resins (18D)
Temperature boundary conditions (3D)

Curing:
Parameters dictating the curing kinetics (8D)
Temperature cycle (1D)

Distortion:
Ply mechanical, thermal, and chemical properties (33)





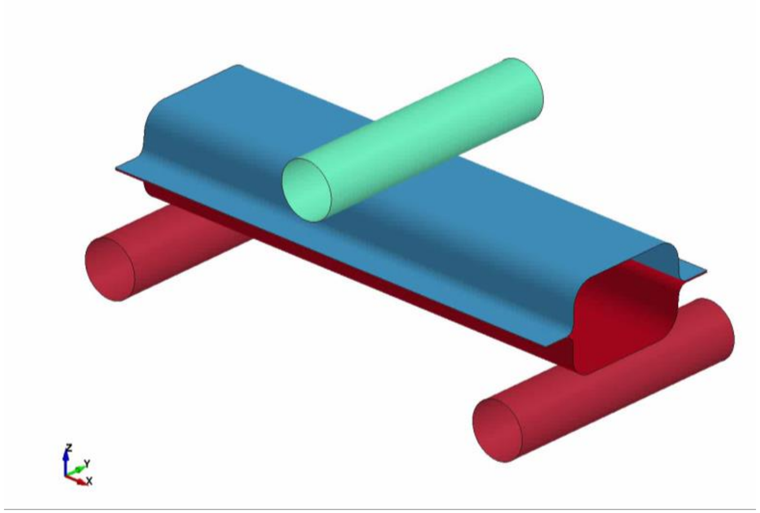


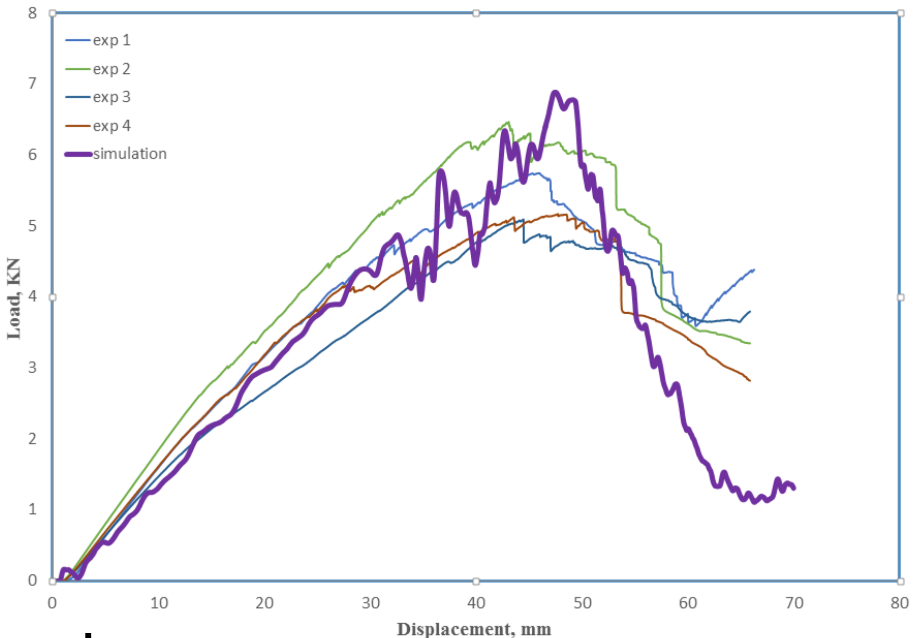
A total of 74 variables were considered in this integrated problem. This problem is computationally challenging and was solved using state of the art methods developed in this project at USC.

Structural Modeling – Accomplishments

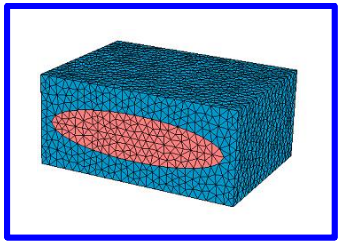
Component validation for a brittle and ductile lay-up
ICME simulation of truncated pyramid (manufacturing and structural behavior)
Created an engineered structural design for the automotive assembly chosen for the demonstration.

Multi-scale Framework Structural Prediction



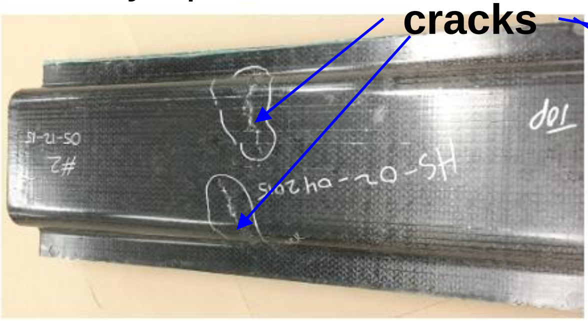


(0/45/-45/90/90/-45/45/0) NCF lay-up

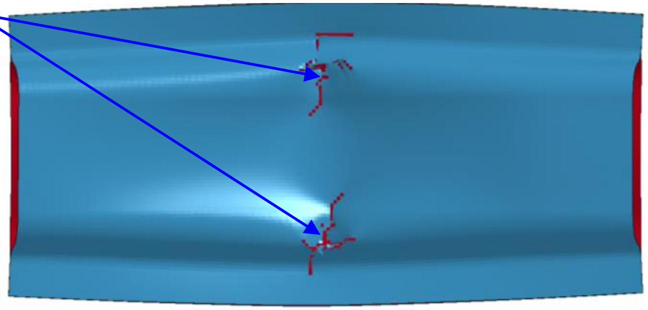


NCF
Multi-scale framework

cracks

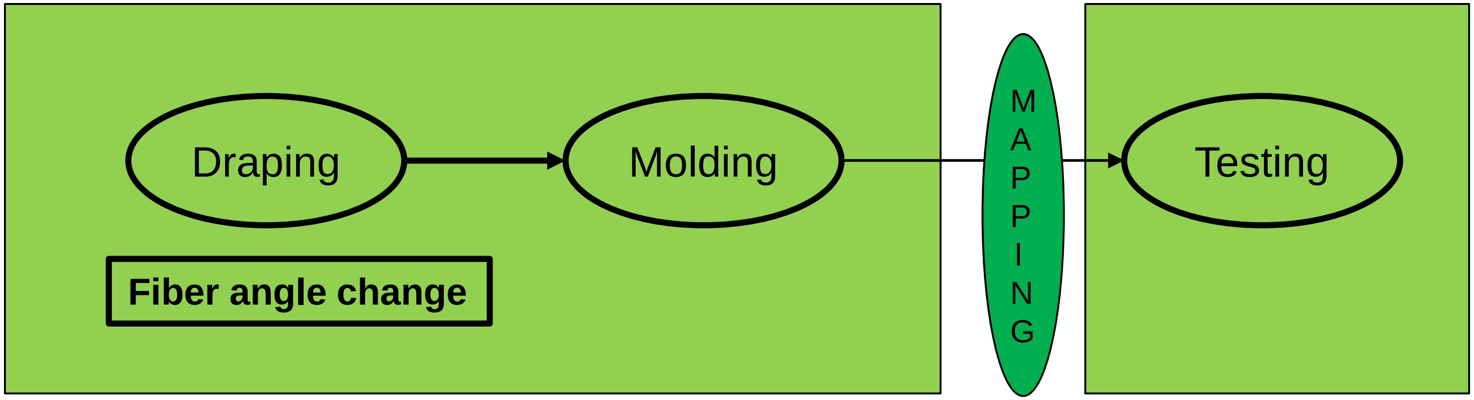


Experiment

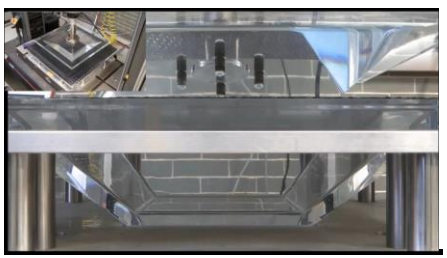


Simulation

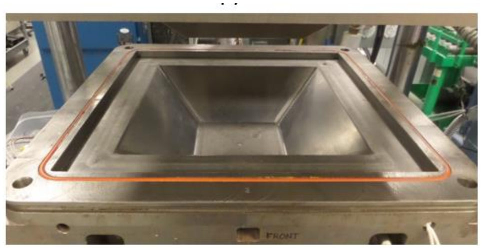
ICME – Truncated Pyramid



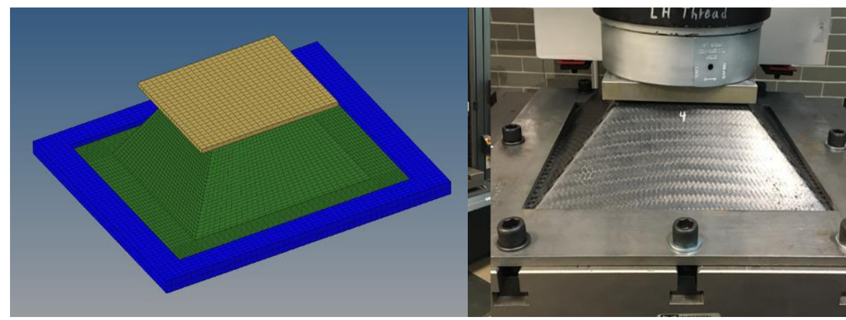
Draping

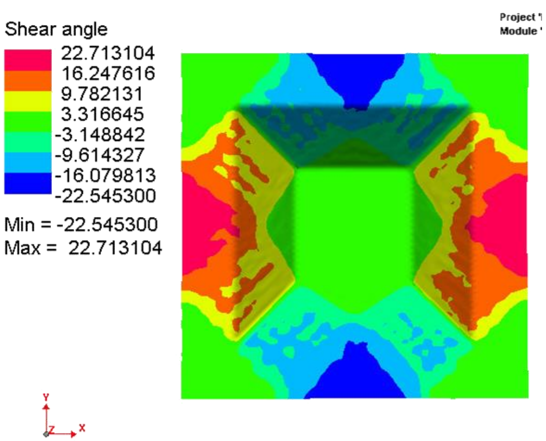


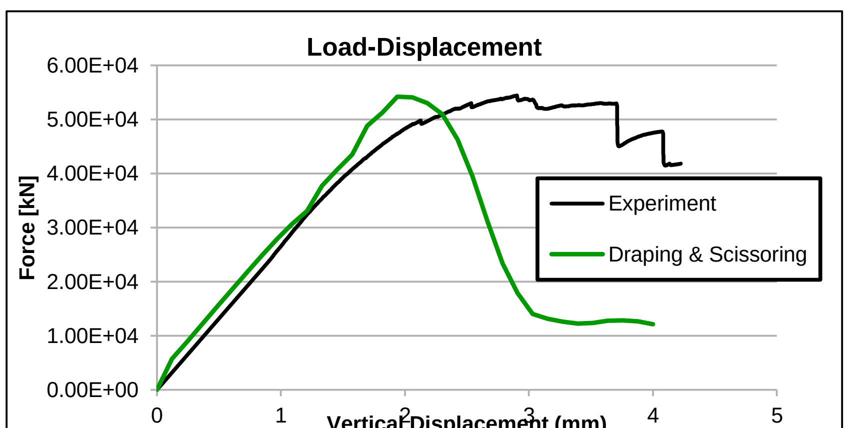
Molding



Structural Performance

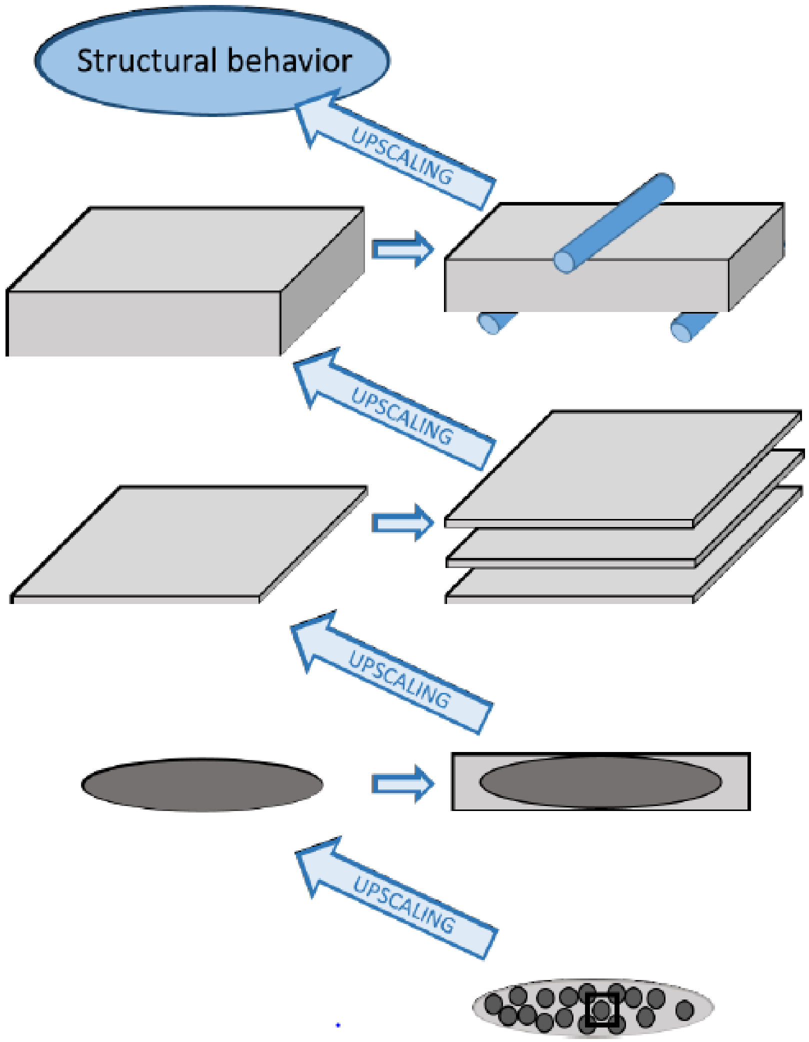






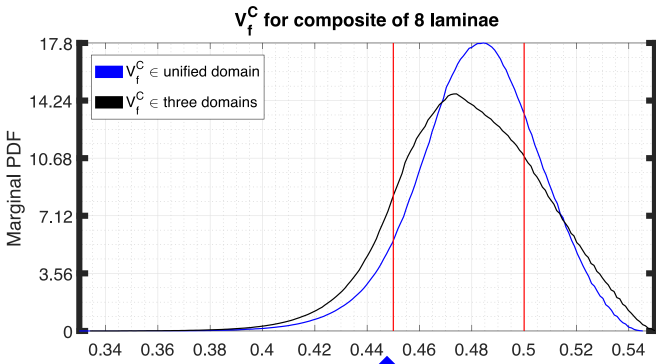
Very good correlations with experiments following ICME process

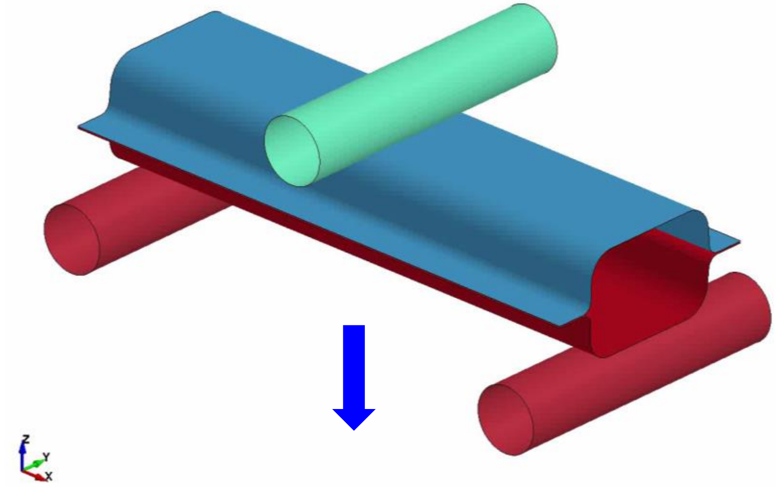
Stochastic Structural Simulation

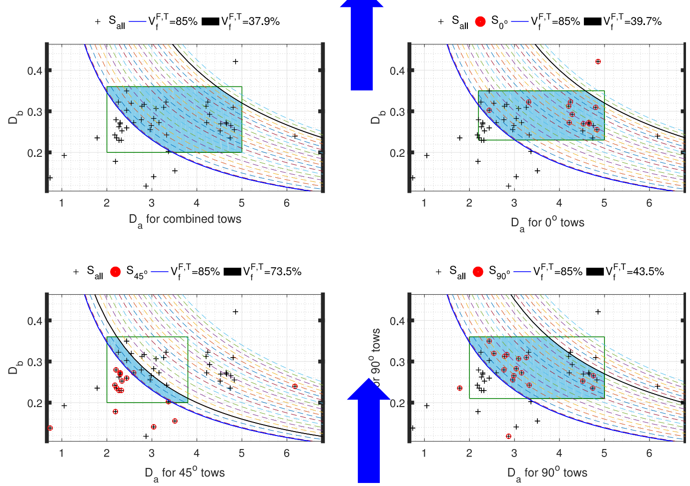


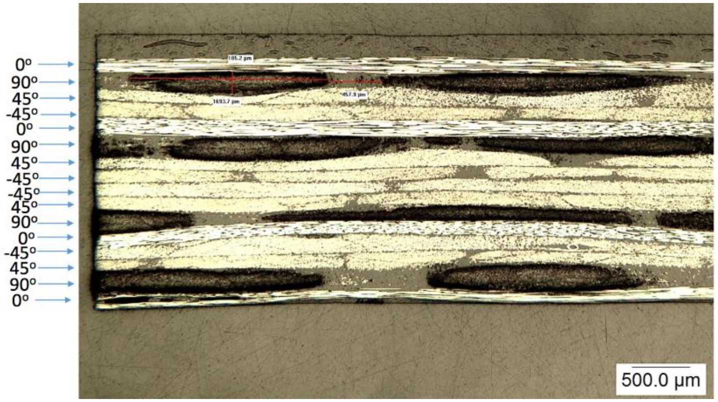
Framework

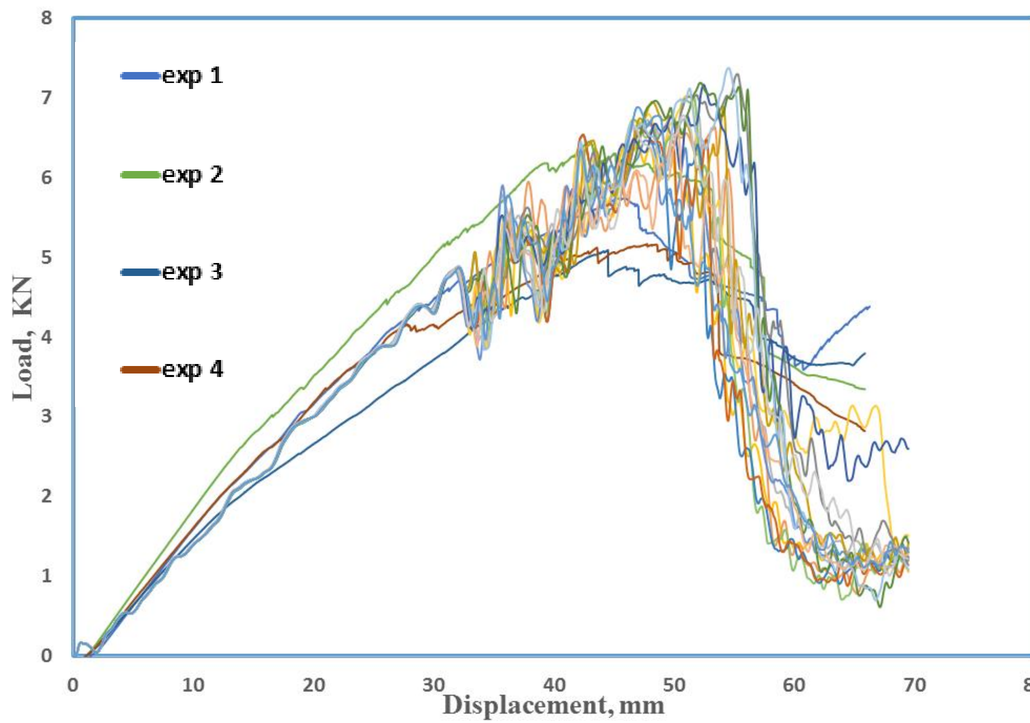
Stochastic Structural Simulation





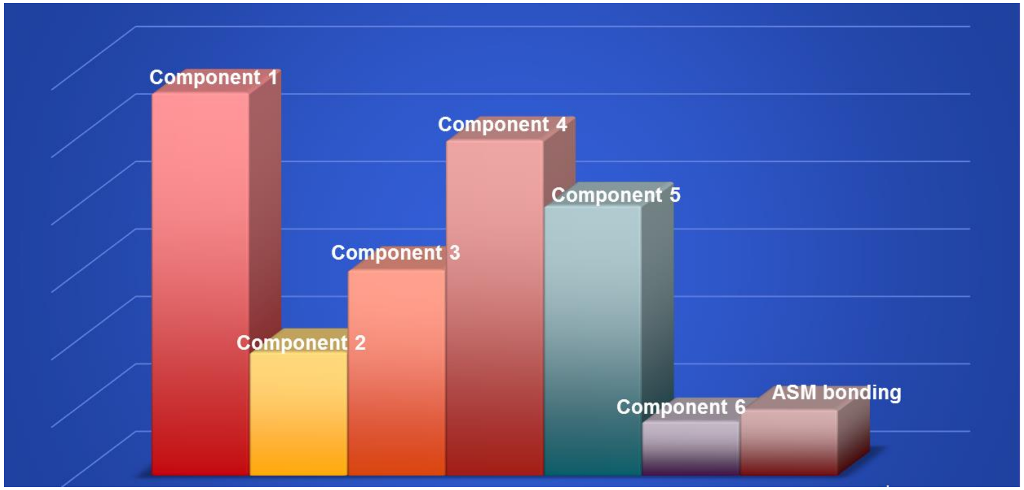




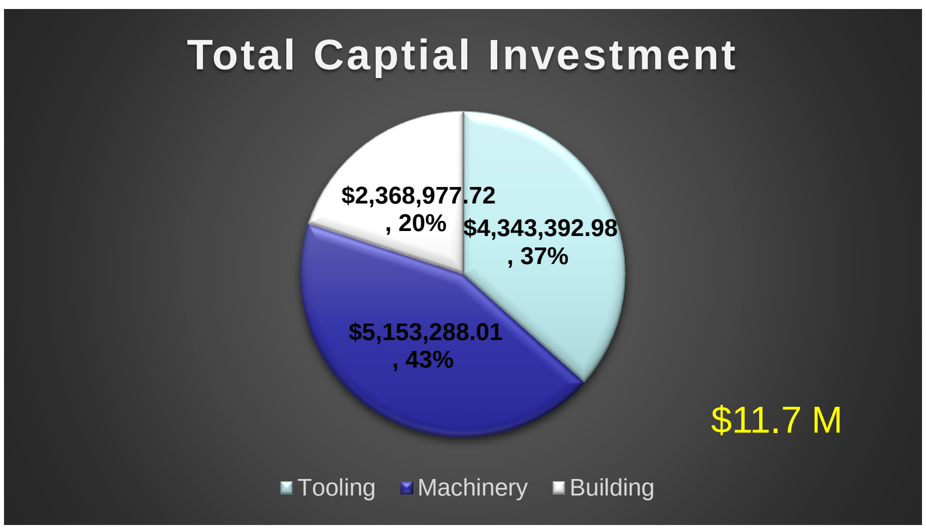


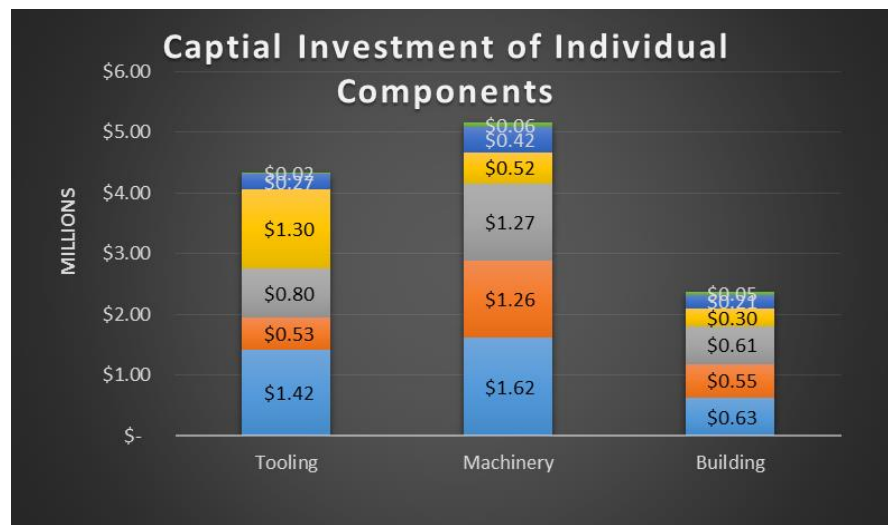
Images are for example only

Cost Modeling



Volume: 80,000/year
Product lifetime: 7 years
Labor: 3 shifts and 5.4 hours in downtime/day
Resin transfer process: HP-RTM
~ 2.8 minutes total cycle time
Capital recovery rate/period: 15%/10 years.
Installation/maintenance :15%/8%
Tool life/materials:1 millions parts, steel base tooling





Current Project - Technology Impact Areas

Materials

- Low cost NCF
- Tow size effects (different K)
- Usage of long fiber thermoplastic for energy absorption
- Stochastics at the micro-scale

Process

- Draping
- HP-RTM/C-RTM, process monitoring and optimization
- Fast curing resins

Structure

- Multi-scale
- Manufacturing effects
- Nonlinear plasticity

Performance

- Integrated performance
- Stochastic performance
- Non-orthogonal weaves
- Crashworthiness

Responses to Previous Year Reviewers' Comments

1. The reviewer wondered whether a model with stochastic simulations always give the same answer, e.g., for energy absorbed during crash, or instead will a model based on stochastic behavior provide a probability distribution of values as the answer.

Answer: The stochastic simulations will give the performance as probability density function with a mean and variation. This will allow us to understand the variables influencing the variation, tail ends of the distribution so that appropriate actions can be taken.

2. The reviewer replied that a number of presentations have been made and that it would be beneficial to the community if the material models generated in this project could be shared and adapted into various commercial software packages..

Answer: Sure, we are putting together all these developments in the commercial programs so that entire industry can benefit from this project.

Partners/Collaborators

General Motors - Prime	Overall project management, execution, baseline performance evaluation, material data generation for manufacturing and structural simulations, assembly of the CF automotive assembly, testing and validation. material database creation for manufacturing and structural simulation, integrate the manufacturing and structural models, develop cost models, demonstrate the technology development.
Continental Structural Plastics (CSP)	Technology supplier, molder - coupons, plaques and components, develop design for manufacturing guidelines, input for cost models.
ESI Group, NA	Manufacturing simulation models for the manufacturing processes chosen in the project.
Altair	Multi-scale simulation models for the structural performance in the LS-DYNA, ABAQUS and Radioss framework.
University of Southern California	Develop stochastic drivers that work for manufacturing and structural performance simulations. Able to utilize the previous work done on a DOE supported work on uncertainty quantification (SciDAC institute).

Remaining Challenges and Barriers

- Comparison of manufacturing process predictions for the HP-RTM and C-RTM.
- Comparison of structural predictions and experimental results for the crash performance of the assembly built for demonstration.
- Certification of the assembly based on the ICME tools developed in the project.

Proposed Future Research

(Any proposed future work is subject to change based on funding levels)

FY 2018

- Build the tooling required to manufacture the automotive assembly
- Fabricate components and assemble them to test under crash sled.
- Collect the experimental data for the manufacturing (HP-RTM/C-RTM) an structural performance (crush load, damage), etc.stochastically.

FY 2019

- Validation of ICME tool - Comparison of prediction and experimental results for manufacturing and structural performance.
- Certification process development.

Summary

- ICME tools – stochastic manufacturing and structural performance tool development is complete and implemented successfully on GM-HPC system.
- Several ICME problems were solved and new results show potential for optimizing the process conditions and performance of the composites.
- A large automotive assembly was designed in a virtual space and released for fabrication. Four major components were designed for high volume manufacturing process (HP-RTM and C-RTM).
- Cost models were developed to understand the future potential research areas for economic improvement

Thank You!

Technical Back-Up Slides

Governing Equations in Injection, Curing and Warpage

Filling – Stage – Coupled flow, heat and cure

Darcy's equation – Fluid Flow $\nabla \cdot \left(-\frac{K}{\mu}\overrightarrow{\nabla P}\right) = 0$

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

Curing Kinetics $\frac{d\alpha}{dt} = \left(A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m\right) \cdot (B - \alpha)^n$

Curing – Stage – Coupled heat and cure

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

Curing Kinetics $\frac{d\alpha}{dt} = \left(A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m\right) \cdot (B - \alpha)^n$

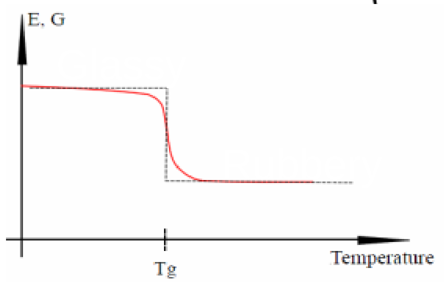
Distortion- Stage (Thermo- Chemical Mechanical Analysis)

$$\sigma_{ij}(t) = \int_0^t C_{ijkl}\big(\xi(t) - \xi(\tau)\big) \frac{\partial\left(\epsilon_{kl} - \epsilon_{kl}^E\right)}{\partial \tau} d\tau$$

$$C_{ijkl}(t) = \begin{cases} 0 & , X < X_{gel} \\ C_{ijkl}^{\infty} + \sum_{p=1}^{P} C_{ijkl}^{p} \cdot \left(e^{-t/\rho_{ijkl}^{p}}\right), X \geq X_{gel} & , \text{no sum on } i, j, k, \end{cases}$$

Di Benedetto function → T_g

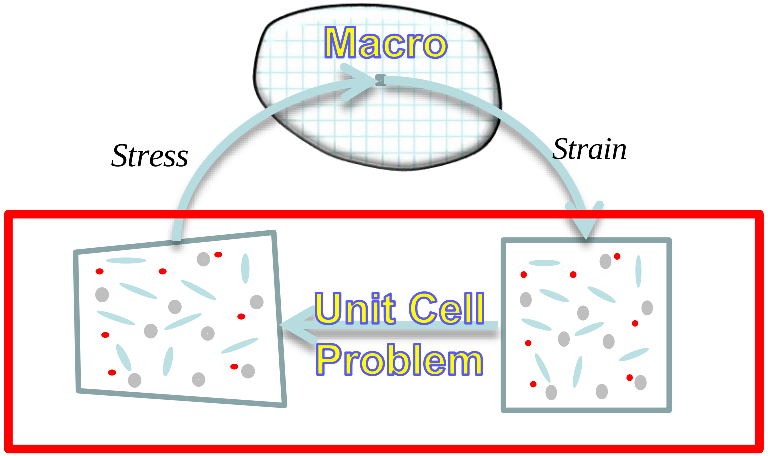
$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda X}{1 - (1 - \lambda)X}$$



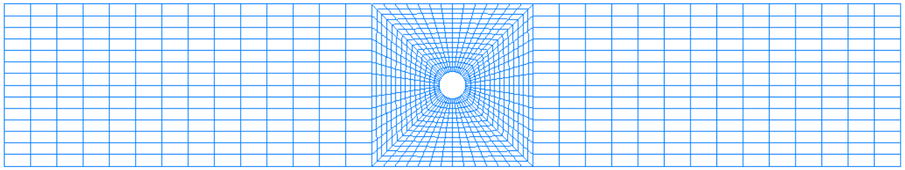
Multiscale Designer Capabilities

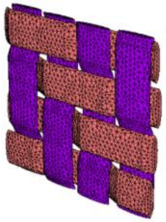
1. Parametric RVE definition
   1) Geometric scripts
   2) User-defined parametric RVE
   3) Integration with experimental data

2. Computational Efficiency: **Speed comparable to single scale model**



3. Size Effect & Softening after Damage





Challenges:
(1) Unit cell size comparable to the hole size and much bigger than macro-element size
(2) Strain softening due to damage

An attempt to account for size effect and softening due to damage

Remedies:
(1) Rescaling of damage models and
(2) Staggered nonlocal multiscale approach